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Theoretical aspects of singly polarized hadron-hadron collisions§ *

Meng Ta-chung

Institut für Theoretische Physik, Freie Universität Berlin
Arnimallee 14, 14195 Berlin, Germany

Abstract

The special role played by singly polarized high-energy hadron-hadron collisions in Spin Physics is discussed: In such processes, the measured and the calculated quantities can be and have been directly compared with each other — without data-extrapolation and without sum rules. It is in this kind of processes, where significant asymmetries (up to 30-40%) have been observed. It is also in this kind of processes, where the obtained data and the predictions of the conventional theories dramatically disagree with each other. Attempts to understand the existing data are briefly summarized. Predictions for further experiments are presented.

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1 Introduction

In this talk I discuss high-energy hadron-hadron collisions in which either the projectile or the target is polarized transversely with respect to the scattering plane. A number of experiments[1-10] of this kind have been performed in the past, among which the elastic proton-proton scattering[1] using polarized target and the inclusive pion-production[2-9] using polarized proton and antiproton beams are probably the most well-known ones — in and outside the Spin Physics Community.

This kind of spin-dependent collision processes is of particular interest for the following reasons:

(a) It is conceptionally simple !

(b) Here, the measured and the calculated quantities, for example the left-right-asymmetries in inclusive pion production, can be and have been directly compared with one another — without data-extrapolation and without sum rules.

(c) A considerable amount of high-energy single-spin-asymmetry data (up to 200 GeV/c incident momentum in laboratory for inclusive meson- and direct-photon production) are now available, and extremely striking features have been observed. Further experiments of this kind will be performed at higher energies — at RHIC, UNK and perhaps also at HERA.

(d) The existing data[1-10] drastically disagree with the theoretical expectations[11] made on the basis of usual (leading twist) perturbative QCD and/or on conventional pQCD-based hard-scattering models. This seems to suggest that mechanisms beyond the usual pQCD may play a significant role in such processes.

This talk will be devided into the following parts. After this introduction, I shall first briefly remind you of the characteristic features of the existing data which are so striking! Then I shall compare these features with the expectations of pQCD and the usual pQCD-based hard-scattering models. After this, I shall discuss some non-perturbative aspects — in particular a simple relativistic quark model.

2 Characteristic features of the existing single-spin asymmetry data

In $p + p(\uparrow) \rightarrow p + p$[1], it is observed that the analyzing power A is significantly different from zero when the transverse momentum ($p_\perp$) of the scattered protons is large [$p_\perp^2 > 5$ (GeV/c)^2 say], and A increases with increasing $p_\perp^2$.

In $p(\uparrow) + p \rightarrow (\pi^0, \pi^+, \pi^-, \eta, \gamma_{dir}) + X$ and $\bar{p}(\uparrow) + p \rightarrow (\pi^0, \pi^+, \pi^-) + X$ [4-10], it is seen that the left-right asymmetry A_N has the following properties:

First, A_N depends strongly on x_F (the Feynman x-variable), but only very weakly (if at all) on $p_\perp$ (the transverse momentum of the observed particle). To be more precise: A_N is consistent with zero near $x_F = 0$ (the central rapidity

region), independent of $p_\perp$[9,10]. But, it becomes nonzero at about $x_F = 0.4$, increases monotonically and reaches up to 40% near $x_F = 0.8$. In other words, the observed[4-8] asymmetry is significantly non-zero in the projectile-fragmentation region. In this kinematical region the asymmetries in the event sample with $p_\perp >$ 0.7 GeV/c are somewhat larger in magnitude than those in the $p_\perp <$ 0.7GeV/c event-sample.

Second, the observed asymmetries[4-8] A_N for π^0, π^+ and π^- are very much different from one another. For example, in $p(\uparrow) + p \rightarrow (\pi^0, \pi^+$ or $\pi^-) + X, A_N(\pi^+) > A_N(\pi^0) > 0$ but $A_N(\pi^-) < 0$. That is, the observed left-right asymmetry A_N is flavor-dependent !

Third, the observed asymmetries depend on the projectile. It is seen[8] in $\bar{p}(\uparrow) + p \rightarrow (\pi^0, \pi^+$ or $\pi^-)$ that $A_N(\pi^+) < 0, A_N(\pi^0) > 0$ and $A_N(\pi^-) > 0$!

Fourth, it has been reported[3] that the left-right asymmetries in the projectile fragmentation region in $\pi^- + p(\uparrow) \rightarrow (\pi^0$ or $\eta) + X$ are consistent with zero.

3 Perturbative QCD and pQCD-based hard-scattering models

What are the expectations of pQCD and the usual pQCD-based hard-scattering models? The relationship between QCD and the polarization of scattered or produced quarks has been discussed already in the late 1970's by G.L. Kane, J. Pumplin and W. Repko[11]. They pointed out that the polarization of scattered or produced quarks in large-$p_\perp$ hadron-hadron collisions can be calculated in pQCD, and according to the usual pQCD calculations the predicted value should be zero (This is because the contribution is proportional to $m_q/\sqrt{s}$, where m_q is the quark mass and $\sqrt{s}$ is the total cms energy which is much much larger than m_q. Note also that for $m_q \rightarrow 0$, there is no helicity flip in the Born diagram or box diagram). Since the individual quark-quark scattering in general produce only a small left-right asymmetry, pQCD necessarily predicts a small left-right asymmetry, independent of the details of the wave function of the quarks in polarized nucleon. These statements apply to exclusive as well as to inclusive processes. Note that since the latter is much easier to describe theoretically, we shall confine our discussions in this talk on inclusive production processes only.

PQCD-based hard-scattering models have been discussed by many authors[11-18]. In this kind of description, the cross section for the inclusive production of large $p_\perp$ pions in $p(\uparrow) + p \rightarrow \pi + X$ can be expressed as a convolution of the elementary cross-section (which describes the scattering of quarks and gluons), the number-densities of the quarks and gluons inside the polarized and the unpolarized protons (spin-dependent and spin-averaged structure functions), and the number-densities of pions in quarks/gluons (fragmentation functions). While the elementary cross sections are calculable in pQCD (provided that the correspond-

ing running coupling constant α_s is sufficiently small), the structure functions and the fragmentation functions are *not* ! The reason is: pQCD is no more valid for soft-processes where long-distance color-interactions play the dominating role. Since leading twist pQCD gives negligible (essentially zero) contribution, it is clear that in order to obtain a non-zero single-spin asymmetry, higher twists must be included in calculating the elementary cross sections, and spin effects need to be introduced into the structure functions and/or the fragmentation functions. Now, let me show you a few explicit examples of such models. In a recent paper[18], M. Anselmino, M. Boglione and F. Murgia reproduced the $p(\uparrow) + p \to (\pi^+,\ \pi^0,\ \pi^-) + X$ data in a model of this type. They assume that the factorization theorem holds in the helicity basis for higher twist contributions and they assume that non-perturbative and intrinsic transverse momentum effects can be properly taken into account in a phenomenological approach. In their model[18], A_N depends on a set of 6 free parameters which appear in spin-dependent structure function $I^{a/p}_{+-}$. The flavor-dependence of A_N for $\pi^+,\ \pi^0$ and π^- is reproduced by choosing different sets of parameters for the u- and the d-quarks. The authors stressed that they have no problems with the time reversal invariance of QCD, because they consider higher twists and they do not exclude soft initial state interactions. The problem of flavor-dependence has also been addressed by A.V. Efremov, V.M. Korotkiyan and O.V. Teryaev[17]. They calculated the single-spin parton asymmetries for high $p_\perp$ gluon and quark production using the sum rules for the twist-3 quark-gluon correlators and the twist-2 distribution function. It is reported in their paper[17] that the difference in sign of asymmetries for π^+, π^0 and π^- production can be reproduced by inserting the empirical values for the spin-contents of the u- and d-quarks $\Delta u = 0.80 \pm 0.04$ and $\Delta d = -0.46 \pm 0.04$ from the polarized lepton-nucleon scattering data are different in sign. Furthermore, higher order elementary interactions and higher twist distribution functions have been used by J. Qiu and G. Sterman[14], and by A. Schäfer, L. Mankiewicz, P. Gornicki and S. Güllenstern[15], where non-zero single-spin asymmetries in $p(\uparrow) + p \to \gamma_{dir} + X$ at large $p_\perp$ have been obtained. Since more about pQCD-based hadron-scattering models will also be discussed by Dr. Teryaev, the next speaker, I shall now change my subject.

4 A non-pQCD approach

A different approach has been pursued by the FU-Berlin group. Instead of performing calculations in pQCD or in the framework of pQCD-based hard-scattering models, they carried out a systematic analysis of all available data directly or indirectly related to the singly polarized hadron-hadron collision processes. They observed that the characteristic features of the asymmetry data have much in common with the typical properties of soft hadronic processes in the fragmentation regions of unpolarized hadron-hadron collisions. Since this

similarity strongly suggests that a considerable part of the mechanisms which are responsible for the observed asymmetries are non-pQCD in nature, they decided to try a non-perturbative approach. In this connection, it is important to note the following:

(I.) Inclusive meson-production in hadron-hadron collision with unpolarized projectile and target have been extensively studied already in the 1960's and 1970's, where in particular, leading particle effect, limiting fragmentation of the projectile have been observed[19] in the kinematical region $x_F \geq 0.4$: In term of quarks, these experimental facts strongly suggest that valence quarks play a dominating role in this kinematical region. In fact, it has been shown[20-24] that part of the mesons observed in this region are due to direct formation (fusion) of the valence quarks of the projectile P and antiquark from the sea of the target T. A natural question that can and should be asked is: Should this be completely different when the *projectile is polarized* ?"

(II.) $A_N \neq 0$ for $x_F \geq 0.4$ means: Transverse motion of the produced meson due to the transversely polarized projectile $P(\uparrow)$ and hence that of of the valence quark in $P(\uparrow)$ is asymmetric. Since this occurs in, and only in, the fragmentation region of the projectile hadron, it is natural to ask: Can this be due to the valence quarks in the transversely polarized projectile ? The answer is "Yes !"; and the reason is : A valence quark can be considered as a Dirac-particle in an effective confining potential (due to the existence of other constituents). Hence, the quantum numbers which characterizes the eigenstates of such a valence quark with given color and flavor are: $(\epsilon\ ,\ j\ ,\ j_z,\ P)$ and in particular $(\epsilon_0\ , 1/2\ ,\ \pm 1/2\ ,\ +1)$ for the ground state. Note that j is the total angular momentum (not the orbital angular momentum because the latter is *not* a good quantum number) !

(III.) It is known that baryon's magnetic moments can be well-described in terms of those of the quarks. In this connection baryons's wave functions can be readily constructed not only in the static quark-model[25], but also in a relativistic quark model. This can be done simply by replacing in the static quark model[25], the Pauli 2-spinors by the corresponding Dirac 4-spinors. In terms of the quark-magnetic-moments, the resulting formulae for the magnetic moments of the baryons in the relativistic quark-model have exactly the same form – independent of the confining potentials. Hence, this baryon-wavefunction describes the baryon-magnetic moments as good (or as bad) as the static quark model[25]. The same wave functions can be used to determine the polarization of the valence quarks in the polarized baryons. In particular, the proton, on the average,[26,27]

$\frac{5}{3}$ of the 2 u-valence quarks are in the same direction
$\frac{1}{3}$ of the 2 u-valence quarks are in the opposite direction
$\frac{1}{3}$ of the 1 d-valence quark is in the same direction
$\frac{2}{3}$ of the 1 d-valence quark is in the opposite direction

This means: There is asymmetry in valence quark polarization; and this asymme-

try is flavor-dependent!! Furthermore, since the wave function of any antibaryon can be readily obtained from the corresponding baryon wave function, the relationship between the results in $p(\uparrow)+p$ and $\bar{p}(\uparrow)+p$ should be predictable.

(IV.) Hadrons are spatially extended objects, and color-forces exist only inside the hadrons. Hence, due to causality, significant surface effects are expected in hadron-hadron collisions in general, and hadronic inclusive production processes in particular. One of the immediate consequences in such production process, in which a valence quark of the projectile and an antiseaquark of the target directly form a system, is the following: Only color-singlet $q\bar{q}$ systems directly formed near the front-surface can acquire extra transverse-momenta due to the orbital motion of the valence quarks (Cf. Fig.1).

Based on these experimental facts and theoretical arguments, the Berliners proposed a relativistic quark-model (BRQM)[26-32], the basis of which are the following:

(I.) Part of the mesons observed in the projectile fragmentations region ($x_F \geq 0.4$) are directly formed by the valence quarks of the projectile – also when the projectile hadron is polarized.

(II.) A valence quark of a hadron can be considered as a Dirac particle in an effective confining potential (due to the other constituents of the hadron). Hence, the ground state of a given quark with a given color and a given flavor can be characterized by its energy ϵ, its total angular momentum ($j=1/2, j_z=-1/2$ or $-1/2$)) and its parity ($P=1$).

(III.) In a relativistic quark model, the wave functions for the baryons can be obtained simply by replacing the Pauli 2-spinors in the static quark model by the corresponding Dirac 4-spinors which describe the ground states of the valence quarks.

(IV) Like all hadron-hadron collisions, "surface effect" should play an important role also in inclusive production processes.

These four points (I to IV) are the cornerstones of the proposed Berliner relativistic quark model BRQM[26-32]. They agree with the existing unpolarized hadron-hadron collision data, because they have in fact been extracted from experimental facts. They agree with the basic properties of QCD — the only candidate for hadronic interactions; yet, they are definitely *beyond* the perturbative QCD regime. The reason is: None of the key concepts which have been used to describe the above-mentioned characteristic properties — in particular neither leading particle effect, nor confining potentials, nor baryon wavefunctions, nor surface effects in hadron-hadron collisions can be described by pQCD.

This model has already been worked out. The calculations and the results can be found in Refs. [26-32]. In this talk, I shall first show you some of the results which can be readily seen without knowing the details.

In order to compare with the $p(\uparrow)+p \rightarrow$ meson $+X$, and $\bar{p}(\uparrow)+p \rightarrow$meson $+X$ experiments where the mesons are: π^+, π^-, π^0, or η the authors use a right-handed Cartiesian coordinate system in which the projectile is moving in the

positive z-direction, the polarization "up" is in the positive x-direction while the origin is fixed at the c.m.s. of the colliding hadron-hadron system. According to BRQM, the following are expected :

(A) In the projectile-fragmentation region of inclusive meson production processes $p(\uparrow)+p \rightarrow (\pi^+\pi^-, \pi^0 \text{ or } \eta)+X$ in which the valence quarks of the upward polarized projectile proton contribute, the produced π^+, π^0 and η go left, while π^- go right.

(B) By using transversely polarized *antiproton* instead of proton-beam, π^0 and η behave in the *same* way as that in the proton-beam case, but π^+ and π^- behave *differently*. They change their roles ! (Cf. Tables 1 and 2).

(C) In the corresponding production processes using pseudoscalar meson beams — irrespective of what kind of target is used and whether the target is polarized — there should be no left-right asymmetry in the projectile fragmentation region.

(D) The asymmetry of the produced mesons is expected to be more significant for large x_F in the fragmentation region of the transversely polarized projectile.

(E) Not only mesons but also lepton-pairs in such experiments are expected to exhibit left-right asymmetry.

The qualitative features mentioned in (A), (B), (C) and (D) agree well with experiments [3-9].

The associations mentioned in (B) and (C) have been predicted [26] before the corresponding data[3,8] were available. The existence of left-right asymmetry for lepton-pairs is a further prediction, which still need to be verified experimentally. Qualitative predictions for other processes such as $p(\uparrow)+p \rightarrow K+X$ and $\bar{p}(\uparrow)+p \rightarrow K+X$ can be and have already been made[30]. It is expected in particular that,

$$
\begin{aligned}
&A_N^{p(\uparrow)+p\rightarrow K^+ +X}(x_F) \text{ should be similar to } A_N^{p(\uparrow)+p\rightarrow \pi^+ +X}(x_F),\\
&A_N^{p(\uparrow)+p\rightarrow K^0 +X}(x_F) \text{ should be similar to } A_N^{p(\uparrow)+p\rightarrow \pi^- +X}(x_F),\\
&A_N^{p(\uparrow)+p\rightarrow K^- +X}(x_F) = 0 \text{ (because } K^- = \bar{u}s)\\
&A_N^{p(\uparrow)+p\rightarrow \bar{K}^0 +X}(x_F) = 0 \text{ (because } \overline{K^0} = \bar{d}s)
\end{aligned}
$$

$$
\begin{aligned}
&A_N^{\bar{p}(\uparrow)+p\rightarrow K^- +X}(x_F) \approx A_N^{p(\uparrow)+p\rightarrow K^+ +X}(x_F)\\
&A_N^{\bar{p}(\uparrow)+p\rightarrow \bar{K}^0 +X}(x_F) \approx A_N^{p(\uparrow)+p\rightarrow K^0 +X}(x_F)\\
&A_N^{\bar{p}(\uparrow)+p\rightarrow K^+ +X}(x_F) = 0 \text{ (because } K^+ = u\bar{s})\\
&A_N^{\bar{p}(\uparrow)+p\rightarrow K^0 +X}(x_F) = 0 \text{ (because } K^0 = d\bar{s})
\end{aligned}
$$

Let me now show you some of the quantitative results. Because of the limited time, I shall not discuss the details, but only show you the following: (α) in Fig.2: comparison between data[4-7] and the calculated result for $p(\uparrow)+p \rightarrow (\pi^+,\ \pi^-,\ \pi^0)+X$, together with the predictions for $p(\uparrow)+p \rightarrow l\bar{l}+X$, and $\bar{p}(\uparrow)+p \rightarrow l\bar{l}+X$. ($\beta$) in Fig.3: the calculated left-right asymmetry A_N as function of x_F for inclusive lepton-pair production using π^--beam and transversely polarized

nucleon and nuclear targets: $\pi^- + p(\uparrow) \to l\bar{l} + X$, $\pi^- + n(\uparrow) \to l\bar{l} + X$, and $\pi^- + D(\uparrow) \to l\bar{l} + X$ for $Q = 4$ GeV/c at $p_{inc} = 70$ GeV/c. (γ) in Fig.4: the calculated A_N as function of x_F for inclusive lepton-pair production using unpolarized proton-beam at 820 GeV/c and transversely polarized nucleon and nuclear targets, $p + p(\uparrow) \to l\bar{l} + X$, $p + n(\uparrow) \to l\bar{l} + X$, and $p + D(\uparrow) \to l\bar{l} + X$ for $Q = 4$ GeV/c.

Note that, while the qualitative results (e.g. those shown in Table 1 and 2 and those for kaon-production listed above) are obtained without any parameters, there is one unknown parameter C in all the qualitative results (e.g. those shown in Figs. 2, 3 and 4). This parameter C characterizes the intensity of the surface effect which ranges from 0 to 1. We found $C = 0.6$ by comparing the calculated curves with one of the data points [4-7] of the reactions $p(\uparrow)+p \to (\pi^+,\ \pi^0,\ \pi^-)+X$ at $p_{inc} = 200$ GeV/c.

5 Concluding remarks

As far as singly polarized hadron-hadron collisions are concerned, experimental research is ahead of theoretical studies. We theoriests need to work harder! Our experimental colleagues can help us not only by giving us more and better data, but also by asking us more critical questions!

The characteristic features of the existing single-spin asymmetry data show that they have much in common with the typical properties of soft hadronic processes observed in the fragmentation regions of unpolarized hadron-hadron collisions. These similarities strongly suggest that the mechanism(s) responsible for such asymmetries are soft in nature. Hence, it is not surprising to see that straight-forward application of usual (leading-twist) perturbative QCD leads to results in dramatic disagreement with the data. The model (BRQM) proposed by the FU-Berlin group serves as an example in which the relations between the characteristic features of the existing data and the non-pQCD aspects of such processes are explicitly given. In spite of its successful description of the existing data and its prediction power, BRQM is just a phenomenological model! Whether — if yes how — this model can be embeded in the framework of QCD — the only candidate for hadronic interactions — is still an open question. It is clear that the theorists have much home-work to do. It is also clear that the experimentalists in the Spin Physics Community have done a magnificent job: Among other things, they remind us theorists that it pays to be open-minded and critical — also towards our favorite toy!

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Table 1: Properties of $\pi^{\pm}$, π^0 or η in $p(\uparrow) + p \rightarrow \pi^{\pm}(\text{or } \pi^0, \eta) + X$

P(sea)—T(val)					P(val)—T(sea)								
P(sea)	u	$\bar{u}$	d	$\bar{d}$	P(val)		u				d		
p_y	0	0	0	0	p_y	$\leftarrow$		$\rightarrow$		$\leftarrow$		$\rightarrow$	
Weight	1	1	1	1	Weight	5/3		1/3		1/3		2/3	
T(val)		d		u	T(sea)		$\bar{d}$		d		$\bar{u}$		u
p_y		0		0	p_y		0		0		0		0
Weight		1		2	Weight		1		1		1		1
Product		$d\bar{u}$		$u\bar{d}$	Product		$u\bar{d}$				$d\bar{u}$		
p_y		0		0	p_y	$\leftarrow$		$\rightarrow$		$\leftarrow$		$\rightarrow$	
Weight		1		2	Weight	5/3		1/3		1/3		2/3	
T(val)		u		d	T(sea)		$\bar{u}$		u		$\bar{d}$		d
p_y		0		0	p_y		0		0		0		0
Weight		2		1	Weight		1		1		1		1
Product		$u\bar{u}$		$d\bar{d}$	Product		$u\bar{u}$				$d\bar{d}$		
p_y		0		0	p_y	$\leftarrow$		$\rightarrow$		$\leftarrow$		$\rightarrow$	
Weight		2		1	Weight	5/3		1/3		1/3		2/3	

Table 2: Properties of $\pi^{\pm}$, π^0 or η in $\bar{p}(\uparrow) + p \rightarrow \pi^{\pm}(\text{or } \pi^0, \eta) + X$

P(sea)—T(val)					P(val)—T(sea)								
P(sea)	u	$\bar{u}$	d	$\bar{d}$	P(val)		$\bar{u}$				$\bar{d}$		
p_y	0	0	0	0	p_y	$\leftarrow$		$\rightarrow$		$\leftarrow$		$\rightarrow$	
Weight	1	1	1	1	Weight	5/3		1/3		1/3		2/3	
T(val)		d		u	T(sea)		d		$\bar{d}$		u		$\bar{u}$
p_y		0		0	p_y		0		0		0		0
Weight		1		2	Weight		1		1		1		1
Product		$d\bar{u}$		$u\bar{d}$	Product		$d\bar{u}$				u$\bar{d}$		
p_y		0		0	p_y	$\leftarrow$		$\rightarrow$		$\leftarrow$		$\rightarrow$	
Weight		1		2	Weight	5/3		1/3		1/3		2/3	
T(val)		u		d	T(sea)		u		$\bar{u}$		d		$\bar{d}$
p_y		0		0	p_y		0		0		0		0
Weight		2		1	Weight		1		1		1		1
Product		$u\bar{u}$		$d\bar{d}$	Product		$u\bar{u}$				$d\bar{d}$		
p_y		0		0	p_y	$\leftarrow$		$\rightarrow$		$\leftarrow$		$\rightarrow$	
Weight		2		1	Weight	5/3		1/3		1/3		2/3	

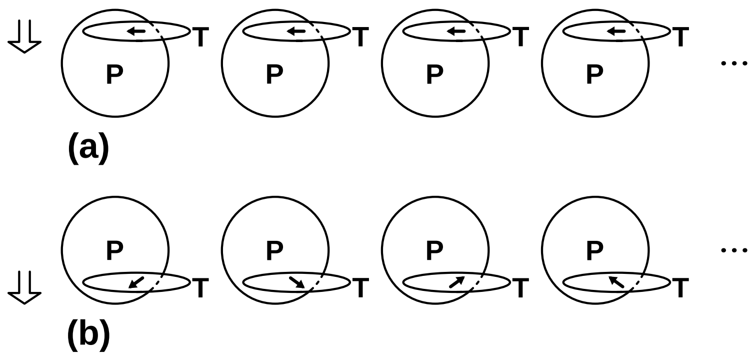

Figure 1:

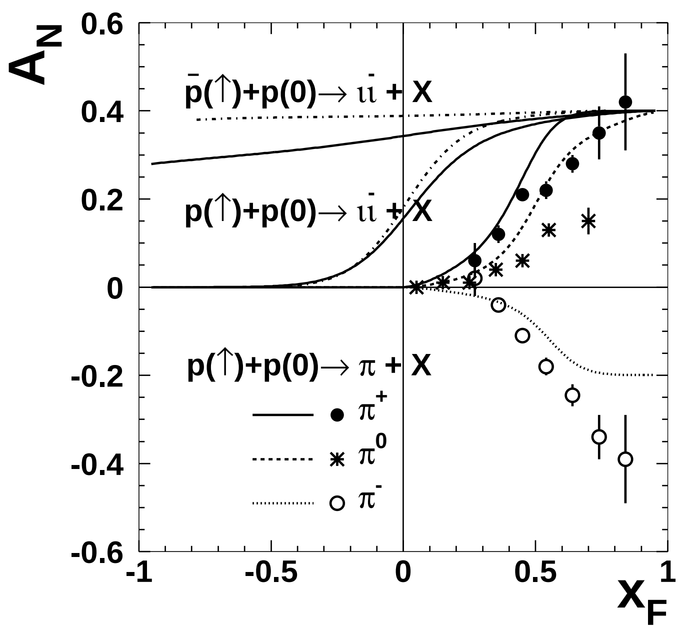

Figure 2:

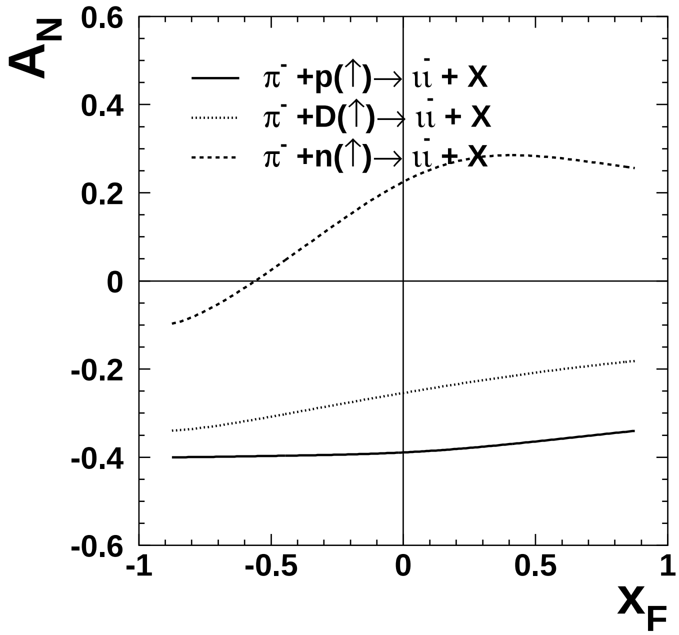

Figure 3:

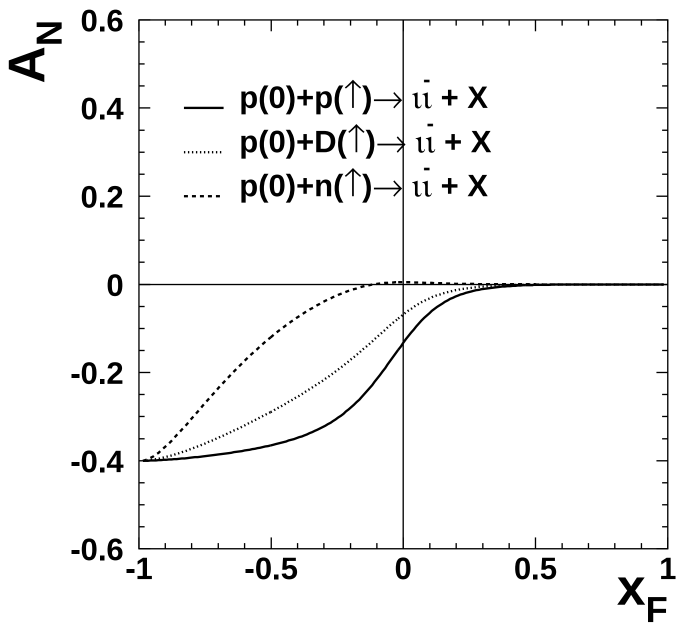

Figure 4: